Precise Orbit Determination for the Shuttle Radar Topography Mission using a New Generation of GPS Receiver

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Abstract

The BlackJack family of GPS receivers has been developed at JPL to satisfy NASA's requirements for high-accuracy, dual-frequency, Y-codeless GPS receivers for NASA's Earth science missions. The first BlackJack flight was on the Shuttle Radar Topography Mission (SRTM) in February of 2000. Data from this mission are being processed to make global maps of the Earth, which will be exploited for scientific and utilitarian purposes. The BlackJack data are used to position the radar antennas with 60-cm (1-sigma) accuracy in each component during the radar data acquisition.

In this paper, we will present the challenges that were overcome to meet this accuracy requirement. These include various bugs in the early version of the receiver software and frequent thruster firings on the Shuttle which degraded the utility of dynamic orbit modeling. We will discuss the various reduced dynamic tracking strategies, Space Shuttle dynamic models, and our tests for accuracy that included a military Y-code dual-frequency receiver (MAGR).

In addition to the Shuttle flight results, we will give the details of tests on newer versions of the BlackJack which will yield positioning at the few cm level for CHAMP [launched July 15, 2000; preliminary results show on-orbit accuracy < 10 cm] and SAC-C missions [Scheduled launch date, November, 2000]. These tests include data taken in orbit, on orbital simulators and with a rooftop antenna. In the rooftop tests, the signal from the antenna is split and simultaneously sampled by a commercial geodetic quality receiver. This test setup allows for comparison to a known standard.

Introduction

The Shuttle Radar Topography Mission (SRTM) was launched on February 11, 2000 from Kennedy Space Center. It's mission was to collect synthetic aperture radar data from 60 deg. north latitude to 54 deg. south latitude and construct a topographic map of land in that region of the Earth. To process the radar data precise knowledge of the Shuttle position is required (60 cm, 1-sigma for each component). To obtain the precise position of the Shuttle, two newly designed GPS receivers were flown with two independent GPS antennas located near one of the radar antennas approximately 60 meters from the Shuttle center of gravity. The new generation of space qualified GPS receiver is referred to as BlackJack.

Pre-launch testing of the BlackJack receivers had shown that in a nominal operation mode the mission required orbit accuracy of 60 cm (1-sigma) in all components could be met with kinematic positioning (information from orbital dynamics is not used) of the antenna phase centers. This testing had shown that

the receivers should track 7 satellites, most of the time, with very few breaks in the carrier phase tracking. In flight, the receivers did not track as well as expected. Receiver 1 typically tracked 4 GPS and receiver 2 tracked somewhat fewer satellites. Radio frequency interference is the suspected cause of the poorer tracking performance. With fewer than 4 satellites tracked kinematic tracking is not possible. A more complicated tracking procedure using dynamical models was pursued to compensate for the unexpected loss of tracking data [Bertiger et al., 1994; Wu et al., 1991; Yunck et al., 1990, 1994] Using reduced dynamic tracking techniques, the mission tracking requirements were met for 100% of the radar acquisitions.

Backup plans for tracking SRTM included both NASA's Tracking and Data Relay Satellite (TDRS range and Doppler measurements) as well as the Boeing Miniature Airborne GPS Receiver (MAGR). Previous testing of TDRS on the Shuttle in a more benign dynamical environment had yielded 1-m radial precision [Rowlands et al., 1997], which would not meet the SRTM requirements, but our testing of the MAGR GPS receiver with a single antenna feed showed its data could meet mission requirements. The MAGR was flown on SRTM with a multiple antenna feed that degraded performance compared to a single antenna feed. Both MAGR and TDRS data could have been combined in the unlikely event that both BlackJack receivers failed.

Receiver Pre-Launch Testing

A space receiver must return accurate data, track and acquire GPS satellites with the expected on-orbit Doppler signatures and track lengths, operate in the anticipated space environment, and survive the launch environment. To verify each of these aspects for the SRTM receivers, several different tests were performed.

Rooftop tests where performed to test data accuracy with actual GPS signals. Tests on a GPS simulator were performed to test the receiver's ability to track GPS spacecraft with the expected Doppler signatures and track lengths observed from the Shuttle orbit. Finally, a set of environmental tests was conducted. Some details on each of these tests are given below.

BlackJack Rooftop Testing

As part of the BlackJack testing, about 30 hours of live GPS satellite tracking were taken from a rooftop in May and July 1999 before they were shipped out for delivery to the Project at Kennedy Space Flight Center, after which time they were no longer available for such testing.

Data from the July rooftop test yielded root-mean-square (RMS) position errors well below 1 meter. The position was solved for as a white-noise process in which the process noise was set to 5 km at each time update (1-sec updates). In addition to testing the accuracy of the Blakcjack data with the rooftop data set, we also wanted to test how good the formal errors (covariance of the position) predicted the accuracy of the solution. In the vertical, which is the most difficult component to determine, the RMS was 30 cm for points with 3-D formal errors of less than 104 cm (60Xsqrt(3), the mission accuracy requirement). Of all the possible points, 96% had formal errors less than 104 cm in 3-D. Data from the May rooftop test yielded a vertical RMS of 26 cm, with 97% of the points below 104 cm 3-D formal error criteria. Our mission goal had been to achieve 104 cm 90% of the time or better. Our formal error test was clearly a bit pessimistic for the rooftop kinematic tests. The mean positions from the May and July tests differed by 15-cm. These data were processed in kinematic mode. As a comparison, the well-understood Goldstone TurboRogue ground receiver was also studied with the same processing techniques for the same time spans, yielding 99.7% data with formal position errors better than 104 cm 3-D, RMS vertical errors of 11 cm, and a mean vertical error of 10 cm. (Note: errors in the east and north components were about one-half those seen in the vertical). For

the Goldstone data, the mean vertical error was probably dominated by the troposphere model which was not adjusted in the solution.

Flight Simulator Testing

A Northern Telecom 2760 10-channel GPS simulator equipped for 10 channels of C/A L1 was used to test the SRTM receivers. With only 10 channels not all of the GPS satellites in view can be simulated. A 24-hour simulation strategy was adopted to more closely match the BlackJack's satellite selection algorithm although this could not be done perfectly. Thus there would be times when the BlackJack might search for a satellite that was not simulated. With long simulator runs, 90-93% uptime was observed. The goal was to reach 93% uptime per receiver so that the joint uptime would be 99.5 % (10 minutes joint downtime per day), assuming uncorrelated joint outages.

Though dual frequency testing was performed from roof antennas and orbiting Doppler testing was done on the single frequency simulator, a peer review expressed concerns about dual frequency orbiting Doppler tracking. A one-day test of the Engineering Model on a dual frequency Northern Telecom simulator at Goddard was performed to address this issue. The receiver showed nominal performance on the dual-frequency simulator with orbital dynamics.

Environmental Testing

The receivers were subjected to three suites of environmental tests. First, electromagnetic compatibility with the rest of the SRTM payload in terms of susceptibility and emissions was verified. Emissions (conducted, radiated) were measured while the receiver was tracking from a rooftop antenna. Susceptibility was evaluated by watching tracking SNR while the test receiver was exposed to various interfering signals. Some tests were conducted while the receiver tracked directly from the roof antenna, others while the receiver tracked signals re-radiated in the test chamber from the roof to a flight-like antenna and through flight-representative cables.

All susceptibility tests were passed except those where the interfering signal was within the GPS frequency bands.

Both flight units were vibration tested, power off, to test for survivability in the shuttle launch profile. The antennas and LNAs were also successfully vibration tested to above expected launch loads.

The flight receivers, antennas, and LNAs were thermal-vacuum tested for at least 60 hours. While tracking from a rooftop antenna, the receivers were subjected to temperatures cycles from +60 to −10 C. They tracked successfully except during the sudden temperature changes (> 1 C/min) experienced during cycle transitions. During these slews, the onboard oscillator changed frequency too quickly for the tracking software to properly compensate. The LNAs were temperature cycled, while operating, from −70 to +70 C, based on thermal models of their OAS (Outboard Antenna Structure) environment and experienced only slight performance degradation at the high end of the temperature cycles. The antennas were temperature cycled, in operation, from −120 C to +70 C with no ill effects or performance degradation, again, based on OAS thermal models.

SRTM In-Flight Receiver Tracking Performance

Both receivers experienced numerous resets and tracked fewer than the expected number (~7) of satellites. This is consistent with in-flight interference. Postflight testing of both SRTM flight receivers with

simulated orbital signals showed receiver tracking performance at the tested pre-flight levels, substantiating the hypothesis of in-flight interference. Testing is currently underway to see if the in-flight performance can be duplicated by introduction of interfering tones into simulator outputs. Receiver 1 typically tracked 4 satellites, while receiver 2 tracked slightly fewer than 4 satellites on average. This necessitated switching the orbit solution strategy from kinematic tracking (requiring 4 or more satellites at all times) to reduced-dynamic tracking. With reduced-dynamic techniques, information on the Shuttle position and velocity can be obtained with simultaneous observations to as few as two GPS spacecraft. (One measurement is necessary for determining the receiver clock.) Fig. 1 shows a histogram of joint data outages for the 2 BlackJack receivers. A common data outage is defined herein as an interval during which both receivers are tracking fewer than 2 satellites. Only joint outages intersecting radar takes and exceeding 10 minutes in duration are plotted. Tests showed that gaps smaller than 10 minutes were easily bridged by our knowledge of Shuttle dynamics (RMS errors during the gap < 20 cm). The total amount of time represented by outages is small compared to the length of the mission. Results from tests (described below) in which spans of good data are artificially deleted suggest that even a 30-minute tracking gap does not compromise the orbit accuracy during the outage by more than 2 meters. RMS errors over the entire span of the data fit would of course be significantly less.
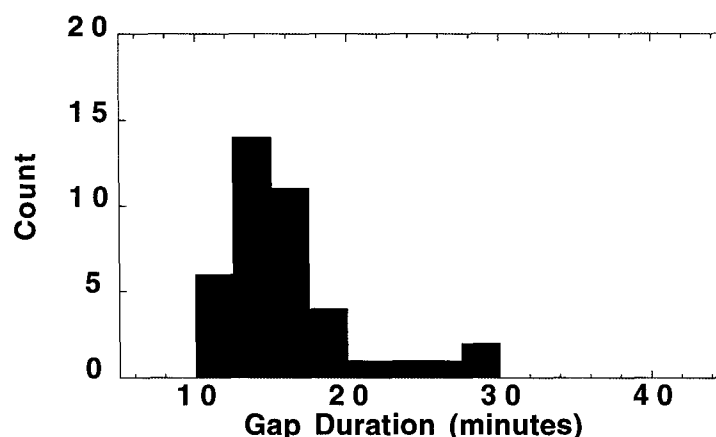

Fig. 1, BlackJack joint data outages during radar data takes on SRTM

Additional Data Problems

There are two additional problems with the BlackJack data collected on SRTM. The first problem, which occasionally affected the phase measurements, was known prior to launch and was fixed in post-processing software. The problem arises when the receiver's model for the phase is off by 25-Hz due to ambiguity in distinguishing this rate from an erroneous sign flip in each data bit ($180°$ per bit × 50 bits per sec = 50 Hz). The error manifests itself at exactly 25-Hz, inducing a conspicuous and anomalous trend in the phase data. With 1-Hz sampling of the phase, the anomalous trends in the SRTM Blackjack data were detected and perfectly corrected by comparing to the pseudorange measurements. The second problem affected the pseudorange measurements and was not known prior to launch. Though the problem could not be fixed with post-processing software, the effects were mitigated by treating the conspicuously affected data as outliers. Known as the "clock nudge" error, the problem stemmed from a bug in the clock correction software of the BlackJack that has since been corrected. Until the receiver is tracking four or more satellites, the internal clock can have a large bias. Once four or more satellites are tracked, the bias on all subsequent channels can be adjusted by integer multiples of 50 nanoseconds (~15 m in equivalent range) through an adjustment ("nudge") of the hardware clock. Data from channels that have already been tracking cannot be

corrected by the hardware adjustment, and the correction is made by the receiver software. The software correction should have been made using the correct integer multiple of 50 nanoseconds, but a "float" was inadvertently used. This resulted in errors of some fraction of 50 nanoseconds for data collected on the channels acquiring satellites after a cold start and prior to the clock nudge.

SRTM Orbit Determination Strategy and Results

Since fewer than 4 GPS satellites were tracked by the receivers at many points in the orbit, a reduced dynamic strategy for orbit determination was pursued [*Bertiger et al.*, 1994; *Wu et al.*, 1991; *Yunck et al.*, 1990, 1994]. In this technique, a dynamic model of the Shuttle is developed and errors in this model are compensated for by estimating a stochastic series of accelerations. Other estimated parameters include, initial position and velocity (epoch state), a nominal drag coefficient, and receiver clock error. Estimates of the GPS spacecraft positions and clock offsets were held fixed to precise values determined a priori with data from about 20 ground sites determined every 30 secs. These "quick-look" GPS orbit and clock estimates have RMS accuracies of better than 20 cm and 0.7 ns respectively [*Muellerschoen, et al.*, 1995].

Shuttle Dynamic Models, Solution Arcs

Various Shuttle dynamic models were tried. All included the JGM-3 70x70 gravity field [Tapley, et al., 1995]. The DTM atmospheric drag model [*Barlier, et al.*, 1978; *Hedin, et al.*, 1974] was used to model drag. Models of the Shuttle shape ranging from a simple sphere to complex collection of many surfaces of the correct size and shape were tried. In the end, given the GPS data strength, the spherical model performed at least as well as the more complex models. A sphere was also used to model solar radiation pressure. The stochastic accelerations were treated as a first order Markov process [*Bierman*, 1977]. Various combinations of correlation time and process noise level were tried. The optimal values were determined by examining the differences in Shuttle position during the overlaps. Due to the poorer than expected GPS tracking, a long time correlation of 15 hours with a process noise 2.5 microns/sec^2 yielded the best results. Much shorter time constants are typically used when the tracking data are better. Since the GPS antennas are approximately 60 meters from the Shuttle center of gravity, the Shuttle attitude must be accounted for. For the SRTM mission there were two star trackers on-board. The time series of quaternions from these start trackers was used to determine Shuttle attitude. On all days of the mission, there was one large trim burn maneuver and on the first day there were two large maneuvers. Since the radar did not take data during these maneuvers, no attempt was made to fit the orbit through each maneuver. A new solution arc was started after each maneuver. Fig. 2, shows two typical solution arcs beginning or ending at a Shuttle trim burn. In addition to separating the solution arcs at the trim burns, there was an artificial break either at midnight or 3 hours before midnight. This enabled comparison of the solution during an overlapping time. Past experience with satellites such as TOPEX/Poseidon [*Bertiger et al.*, 1994] for which there were independent tracking systems have shown that the orbit differences during these overlaps can be a good indication of orbit accuracy. This is particularly true if the duration of the overlap is short in relation to the arc lengths of the two participating solutions and if there are sufficient dynamics to make the overlapping estimates of the Shuttle position nearly independent. The long time correlation used for the stochastic accelerations tends to make these to solutions more independent.
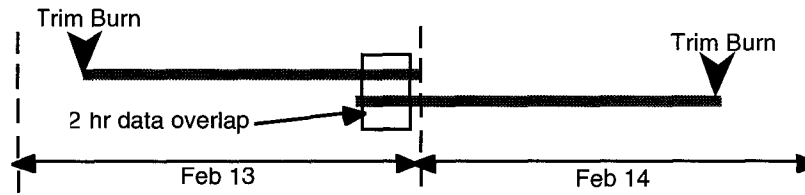
Fig. 2 Two typical SRTM solution intervals.

SRTM Accuracy and Precision

Several tests of accuracy and precision were made for SRTM. These included overlap comparisons, post-fit BlackJack measurement residual analyses, comparisons to selected BlackJack kinematic-determined positions, and comparisons to the MAGR-determined Shuttle orbit.

Fig. 3, shows the RMS differences of overlapping BlackJack-determined orbits spanning the mission radar takes from February 12–20, 2000. The statistics are taken over the central 2 hours of a 3-hr overlap from 21 to 24 UTC on each day of the mission. (see Fig. 2). The differences are shown in radial (center of the earth to the Shuttle), along track (approximately the direction of the Shuttle velocity vector), and cross track (perpendicular to the orbital plane) components. The differencesin each component are typically less than 50 cm. With the BlackJack GPS data sampled every 30 seconds, these solution arcs typically had RMS observation residuals of 1.7 cm in dual-frequencyphase and 1.1 meters in dual-frequencyrange. Note that some nudge errors were surely undetected in outlier criteria and contribute to the high range residuals. The GPS antennas are at the end of a 60 meter boom which oscillates with an amplitude of about 5 cm. Although this effect was measured and accounted for when processing the radar data, it was not accounted for in processing the GPS data since it is of relatively high frequencyand thus should not alias into our reduced dynamic model. It may, however, increase the size of phase residuals.
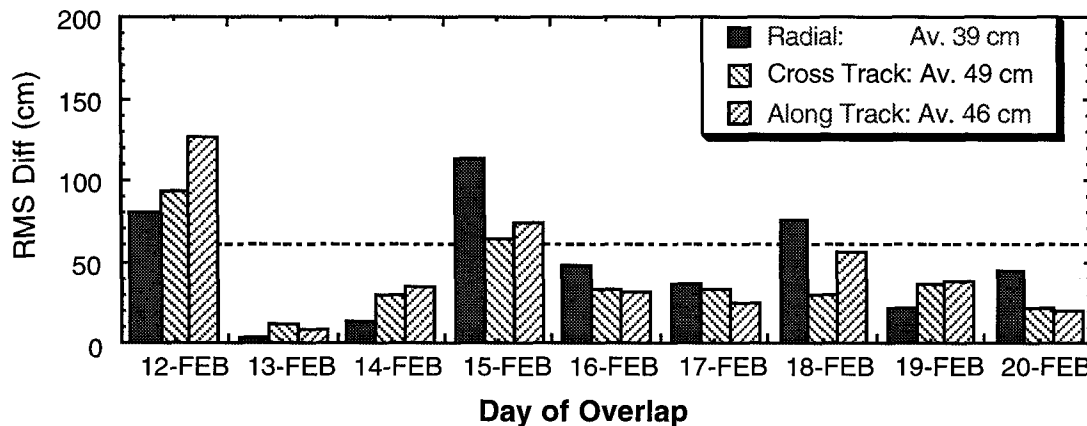

Fig. 3 RMS overlaps using data from both BlackJack receivers to test orbit accuracy, RMS phase residuals 1.7 cm, range residuals 1.1 meters.

Although the BlackJack receivers did not track 4 or more GPS much of the time, there were times when a sufficient number of satellites were tracked to determine the position of the antenna phase center

geometrically (kinematic positioning). The kinematic solution can be constructed by setting the process noise on the 3-D accelerations in the reduced dynamic solutions to an extremely large number (1 m/sec^2). The solutions are then edited to include only points whose formal errors are less than 50 cm. The 50-cm formal errors reflect the random errors due to the assigned data noise of the phase and pseudorange (1 cm phase, 1 meter range) and the observing geometry. We refer to the reduced set of data as "super-edited". This kinematic positioning with super-edited data is dominated by errors in range since the arc lengths are quite short (not much time to average out range errors with phase data). Although it will be less precise than the reduced dynamic solution, it does test for any biases in the reduced dynamic system and an overall sanity check. Fig. 4 is a histogram of the height(radial) differences in the position with the BlackJack reduced dynamic position. The mean is 0.0 meters showing there are no significant biases in the solution. Fig. 5 shows that the 3D distances between the super-edited kinematic solutions and the reduced dynamic solutions are at the meter level. The level of agreement is roughly consistent with the 50 cm formal errors and the known systematic errors in the range (e.g., multipath, nudge).
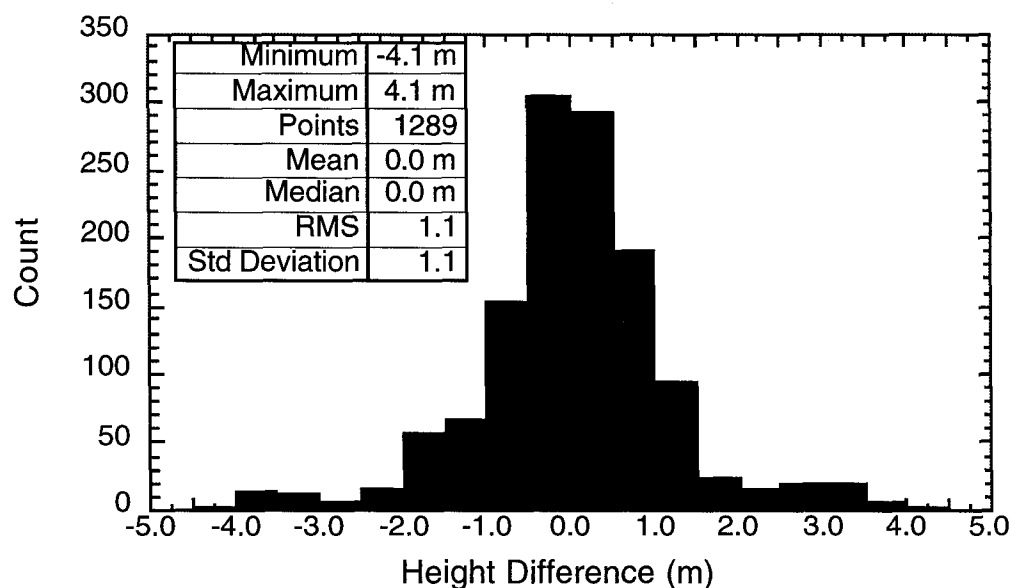
Minimum	-4.1 m
Maximum	4.1 m
Points	1289
Mean	0.0 m
Median	0.0 m
RMS	1.1
Std Deviation	1.1

Fig. 4 Differences in height (radial) super-edited kinematic positioning versus final reduced dynamic orbit.

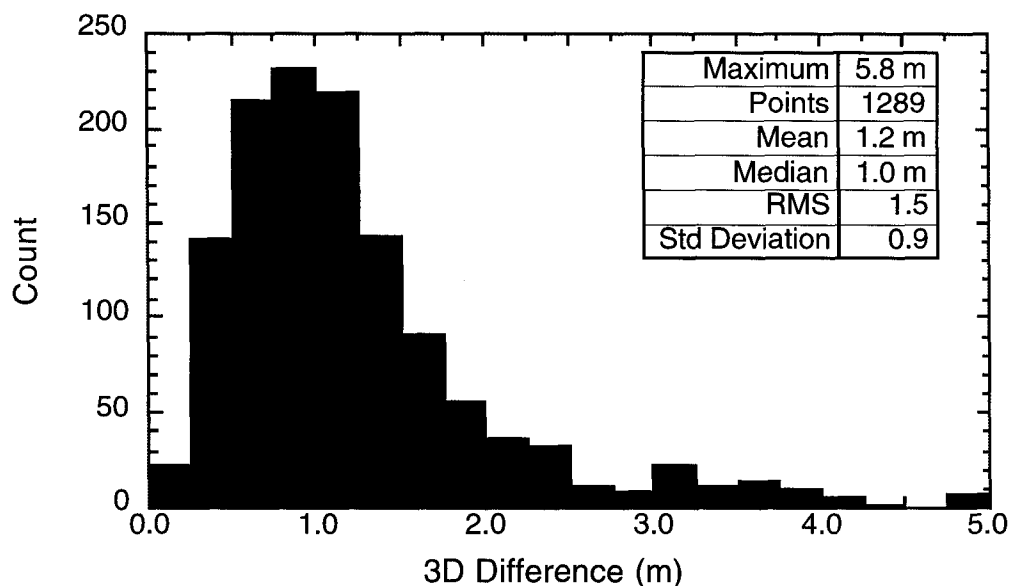| Maximum	5.8 m
Points	1289
Mean	1.2 m
Median	1.0 m
RMS	1.5
Std Deviation	0.9

Fig. 5 Distance between super-edited Blackjack kinematic solution and the BlackJack reduced dynamic solution.

As a final check on orbit accuracy, the MAGR data were used to obtain the best possible reduced-dynamic solution independent of the Blackjack data. The Shuttle has two antennas feeding the MAGR, one above the crew cabin and one below the crew cabin separated by about 5.5 meters. The signals from the two antennas are combined before being fed into the single MAGR antenna input. This allows a full sky view, but introduces very large multipath errors. Through examination of the MAGR SNR levels it is believed that there is as much as a 30-degree common view between the antennas [Murray, 2000]. The MAGR receiver is a 5-channel receiver in which one of the channels roves. The roving channel is used to make measurements of P2 range (it is a military keyed receiver) to periodically calibrate the ionosphere. Continuous measurements of accumulated phase are not available. The 4 tracking channels choose the GPS to track based on optimizing PDOP (position dilution of precision), thus typically tracking at low elevation angles. In this case, it also means that much of the time the signal arrives through both antennas. With significant signals from both antennas, we cannot expect kinematic MAGR solutions to be unbiased. In Fig. 6, we show the RMS differences between the MAGR reduced-dynamic solutions and the BlackJack reduced-dynamic solutions. The solution arcs are labeled with the day in February (F for February) and followed by a colon (:) and a data arc number for that day (typically splitting at trim maneuvers again). RMS differencesare typically below 3 meters with the largest differenceson two adjacent arcs that had a common 3-hour gap in MAGR data. We believe the overall level of the MAGR vs. Blackjack orbit differences can be explained mostly by the large multipath effects of the dual MAGR antenna arrangement.
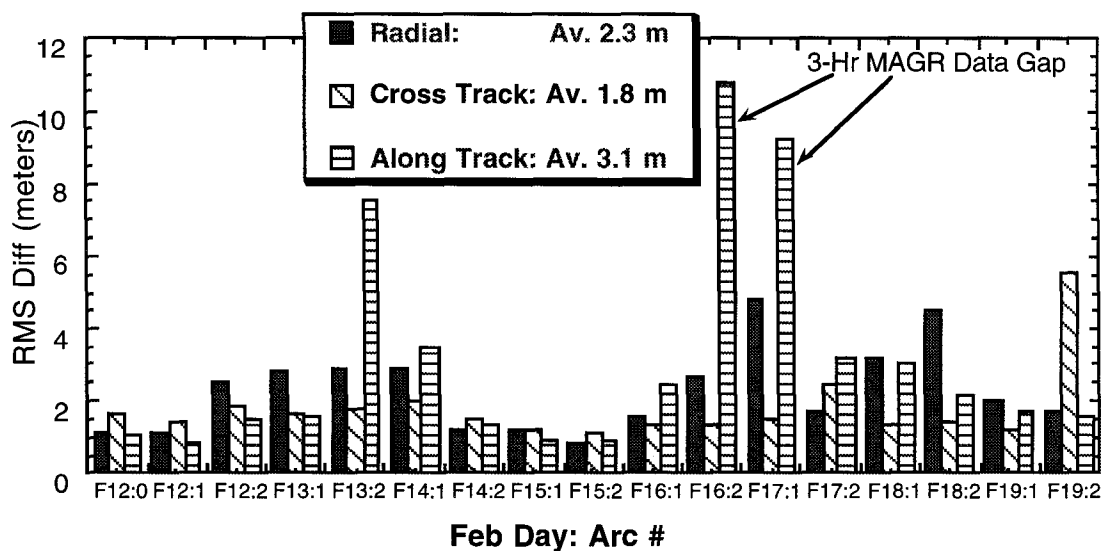
Fig. 6 RMS Difference MAGR (Two Antenna Input Mode/Large Multipath) Determined Orbit versus BlackJack Reduced Dynamic Solution

Effects of 30-minute data gaps

As shown in Fig. 1, the largest interval without GPS data had a duration of 30 minutes. There were two such large gaps in the entire mission. To test the orbit accuracy during these data gaps 30 minutes of data were deleted from Feb. 18, 21:30 to 22:00 of the data arc starting on Feb. 18 21:00 and ending on Feb. 19, 20:35. Since there is no data before 21:00, this is a more stringent test than deleting data in the middle of a solution arc. The solution with the 30-minutes of deleted data were compared to the solution with all the data. In the 30-minute gap, the position agreed to an RMS of 0.73, 0.92, and 1.8 meters in radial, cross, and along track components.

Current BlackJack Performance, CHAMP, SAC-C

Ground Tests Summer 2000

The BlackJack performance has improved steadily since the conclusion of the SRTM mission. In addition to having fixed the clock nudge problem, the BlackJack developers are engaged in an ongoing effort to reduce the numbers of receiver resets. When the effort was initiated in June, 2000, the receivers typically reset 6–10 time daily, resulting in a loss of 5–10 minutes of data each time. It should be noted that intentional system resets triggered by the software are a feature of the BlackJack's fault-tolerant design, intended to deal gracefully with receiver anomalies arising from various conditions in the space environment, such as single-event upsets. At issue here, however, are potential programming errors that trigger resets inadvertently. A goal for satisfying the requirements of the balance of the NASA high-accuracy scientific missions (e.g., Jason-1, ICESAT) is to reduce these inadvertent resets to less than one per day. At this writing, the average number of daily resets has been reduced from 6–10 to less than three, so significant progress has already been made.

Comprehensive tests of the radiometric data quality are performed on the ground data collected at JPL as

part of the software improvement effort. Dozens of receiver days of data collected by a rooftop antenna have been analyzed using a variety of tests, including both static and kinematic precise positioning. The kinematic tests, wherein the position of the antenna is determined freely and independently at each measurement time, is particularly demanding. These tests currently yield geocentric estimates of the antenna height which are accurate to 3–4 cm RMS with approximately 98% coverage in time. This represents a significant improvement relative to the results from the rooftop kinematic tests (described previously) performed prior to the launch of SRTM.

Preliminary CHAMP On-Orbit Performance

CHAMP is a German spacecraft [http://op.gfz-potsdam.de/champ] which carries a BlackJack receiver whose software has been updated compared to the SRTM receivers. It was launched on July 15, 2000 into an orbit at an altitude of 450 km. A reduced-dynamic solution was computed with the 4 days of data, July 30 - August 2, received from CHAMP. Note that although selective availability (SA) was turned off after SRTM and before CHAMP, our use of GPS post-processed orbit and clock values completely eliminate any effects of SA. Four data arcs were used starting 3 hours before midnight and ending 27 hour later at midnight the next day. As described above, the estimated positions from adjacent orbit solutions were compared during overlapping time periods. The typical RMS overlap was below 10 cm in each component. On one of the days, there was Satellite Laser Ranging (SLR) data available from two ground stations. The BlackJack determined position was used to compute the residual to the laser range measurements at each of these stations. Table 1 shows the statistics on the residuals of the normal pointed laser data recorded every 5 seconds. No parameters were adjusted to fit the laser data. These tests independently verify orbit accuracy to better than 10 cm. When these data were processed, star tracker and accelerometer data from CHAMP, which is still in its technical commissioning phase, were unavailable. The star tracker data will improve the attitude model and the accelerometer data would improve the dynamic model.

Site	Number of 5 Second Points	Mean(cm)	Standard Deviation(cm)
Grasse, France	54	9.8	6.6
Yaragadee, Australia	17	-1.5	2.6

Table 1, Satellite Ranging Residuals to the BlackJack determined position of CHAMP.

Summary

The SRTM mission position requirements of 60 cm RMS errors per component were met and validated through a variety of tests including orbit overlaps (< 50 cm per component), data residuals (1.7 cm phase, 1.1 m range), and comparison with independent measurements of position obtained by the MAGR GPS receiver. Stringent tests of the reduced dynamic solution against highly selected geometric positioning of BlackJack phase center further demonstrated that there were no significant biases in the solution. SRTM was the first successful flight demonstration of the BlackJack technology. It has since been demonstrated with significantly improved performance on CHAMP. Performance is expected to improve further and be verified by subsequent ground testing and flight testing.

Acknowledgments

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BlackJack GPS on SRTM
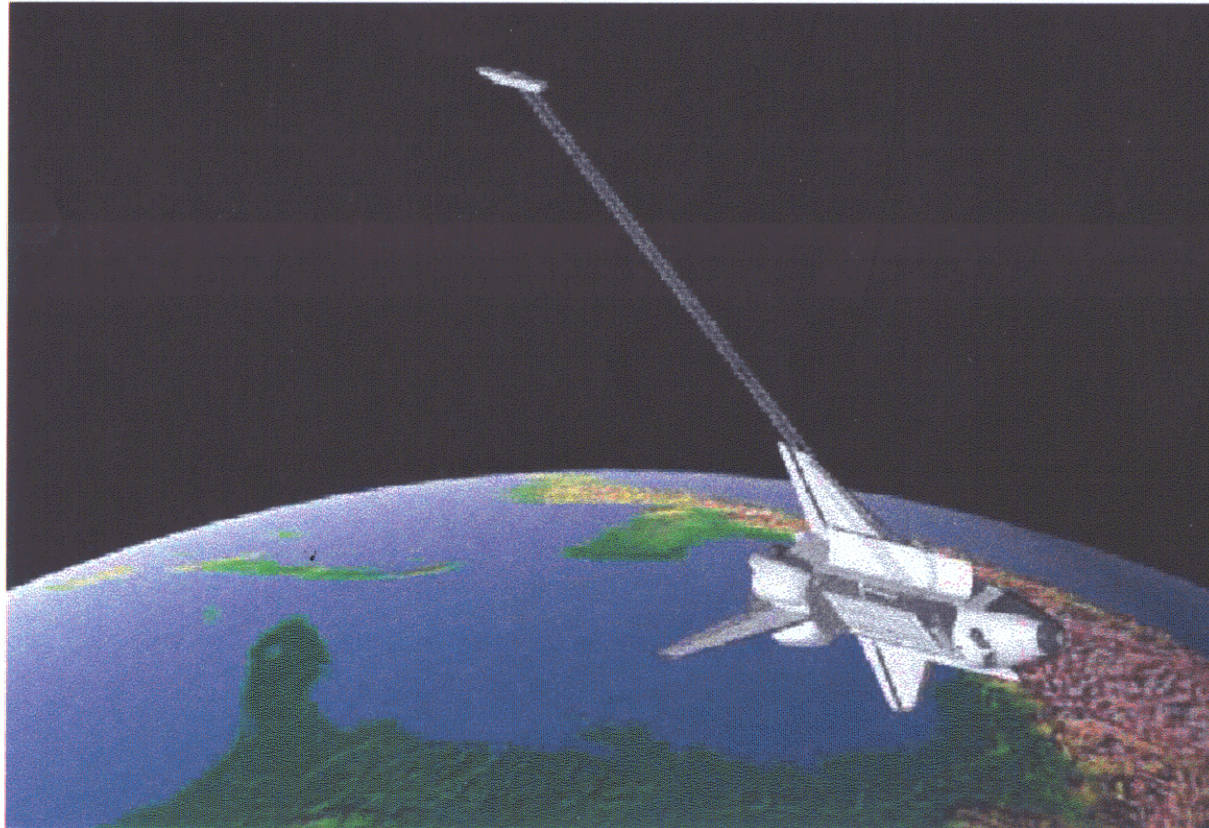
- **SRTM represents first flight of JPL Blackjack receiver**
  - High-accuracy, dual-frequency, Y-codeless GPS receivers to support NASA mission science requirements.
- **SRTM accuracy requirement: 1 m in all 3 axes, 1.6 σ**
  - **0.6 m per component (1 σ)**
- **SRTM map accuracy 16 m vertical 20 m horizontal (1.6 σ)**

Blackjack/SRTM mission statistics

- **Receivers (2) possibly experienced RF interference**
- **Tracked up to 7 GPS simultaneously but ~4 more typical**
- **Solutions provide 100% coverage of radar takes**
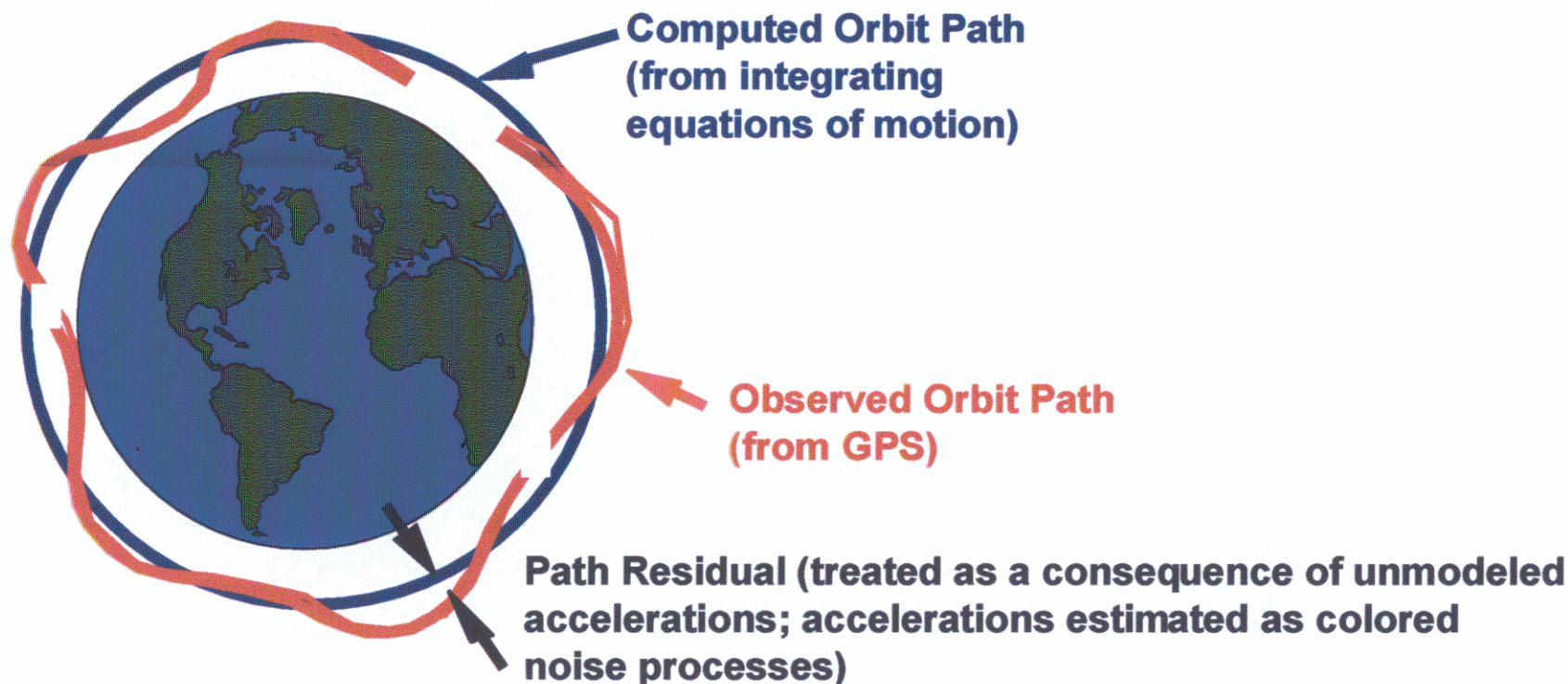- **POD solutions meet requirements**

GPS POD for SRTM
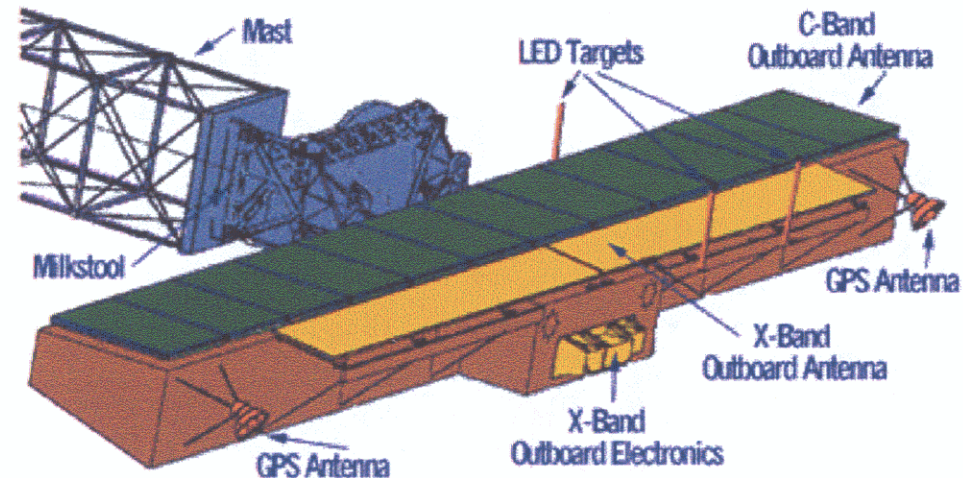
- Due to deficiency in number of GPS tracked, geometry not generally robust enough for kinematic (geometric) positioning.
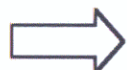
⇨ Problem: not possible to adequately model complex dynamics (e.g., drag, thruster firings).

- Solution: "Reduced-dynamic" tracking

Computed Orbit Path (from integrating equations of motion)

Observed Orbit Path (from GPS)

Path Residual (treated as a consequence of unmodeled accelerations; accelerations estimated as colored noise processes)

- **Complex shuttle dynamics (230 km altitude)**
  - Recovered accelerations are typically 3 orders of magnitude larger than those from Topex/Poseidon (1300 km altitude)
  - Small thruster firings nearly constant occurrence
  - Reduced Dynamic Stochastic Accelerations: 2.5×10^{-6} m/sec^2 with 15 hour time constant
- **Blackjack receiver software errors(fixed in current version)**
  - Nudge
  - 25-Hz
- **Complex data combinations**
  - Data from both receivers processed together
- **MAGR Data**
  - Checks, increased coverage
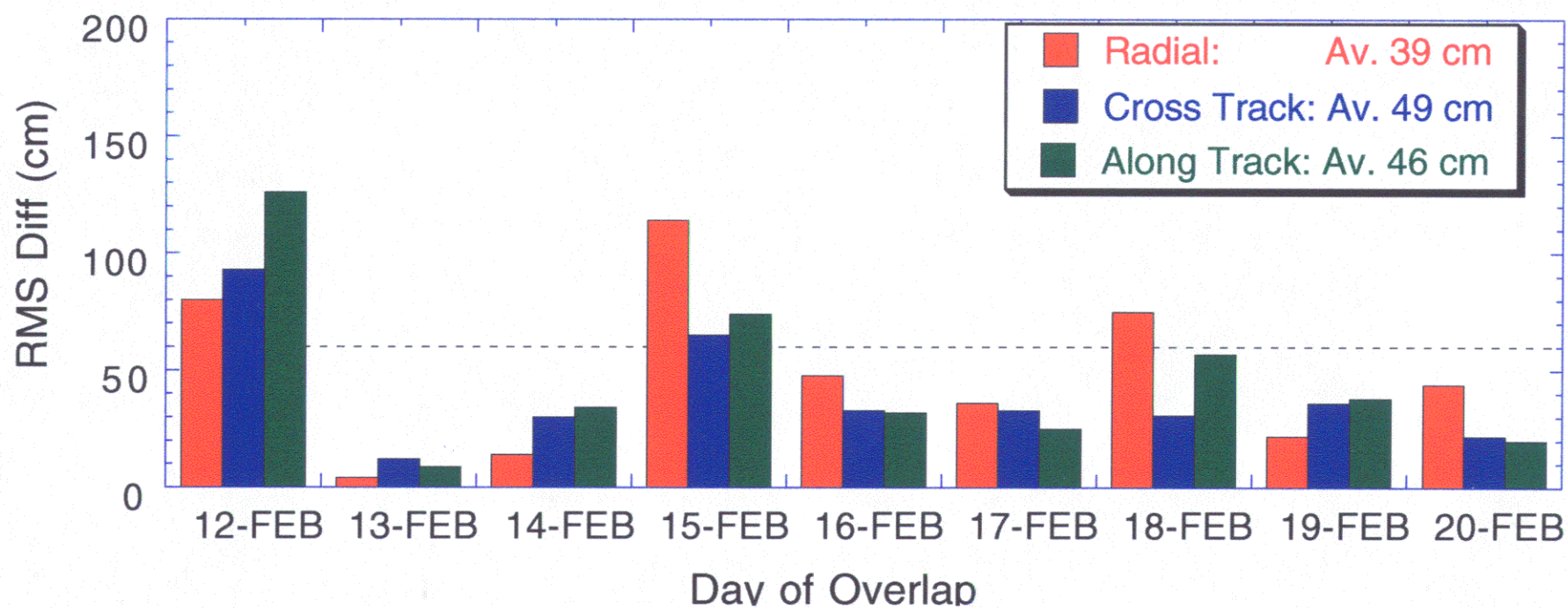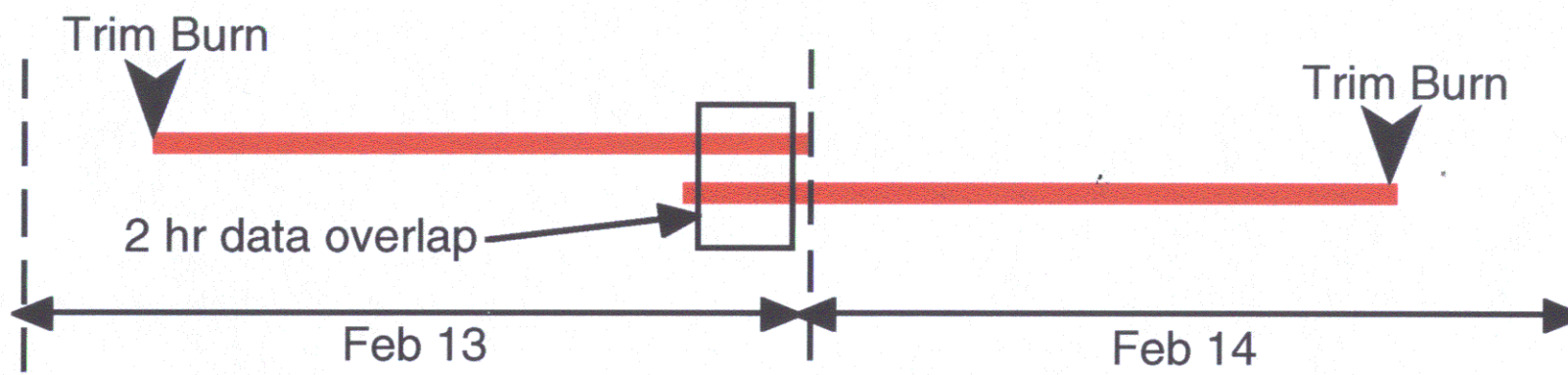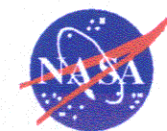 - Serious multi-path errors with MAGR antenna system

- ## SRTM BlackJack specific

  - Formats

  - 25-Hz detection and correction

- ## MAGR data handler/editor

  - Channel biases

  - Ionosphere Calibration

- ## GOA II multiple antenna options

Outages Intersecting Radar Takes
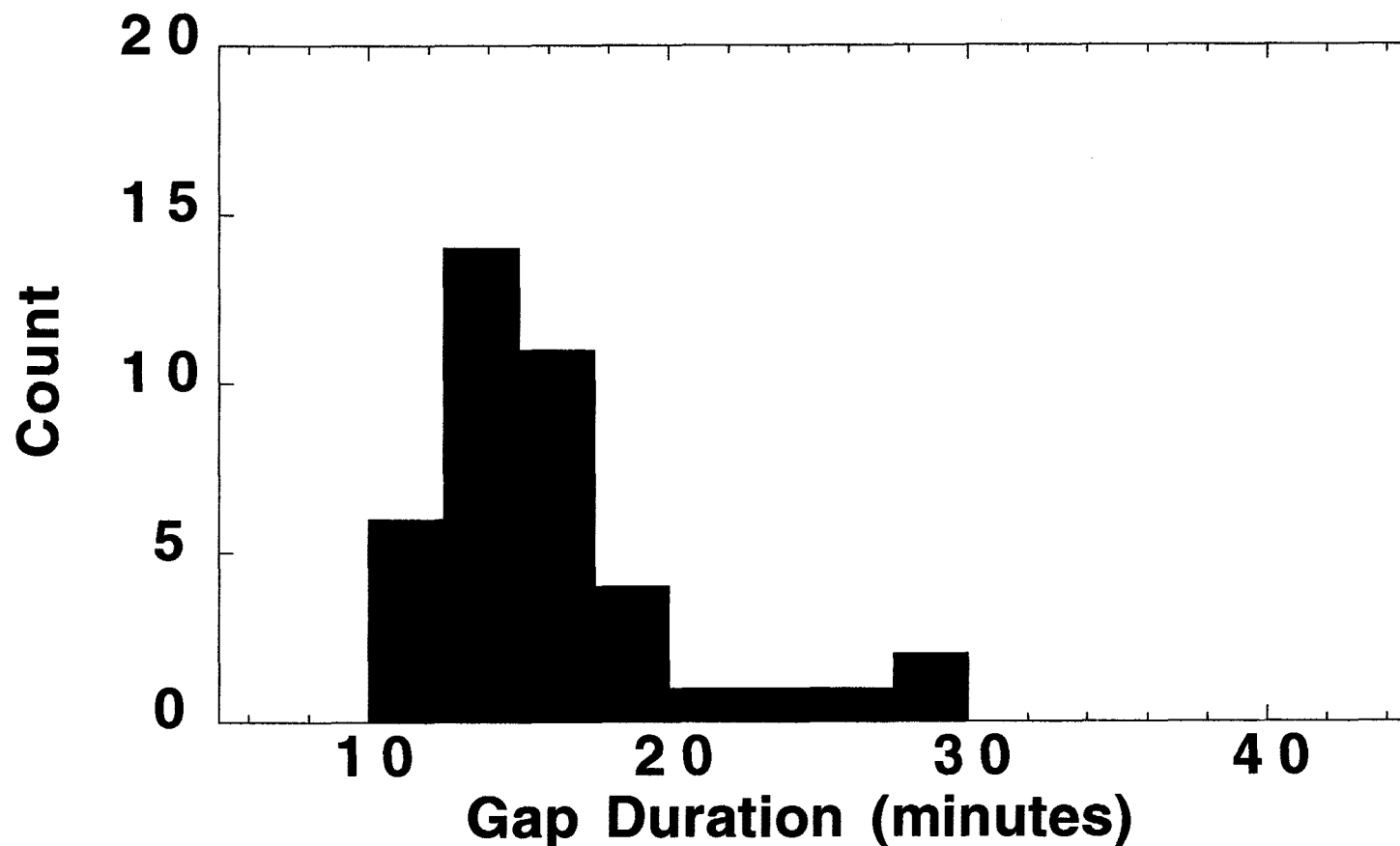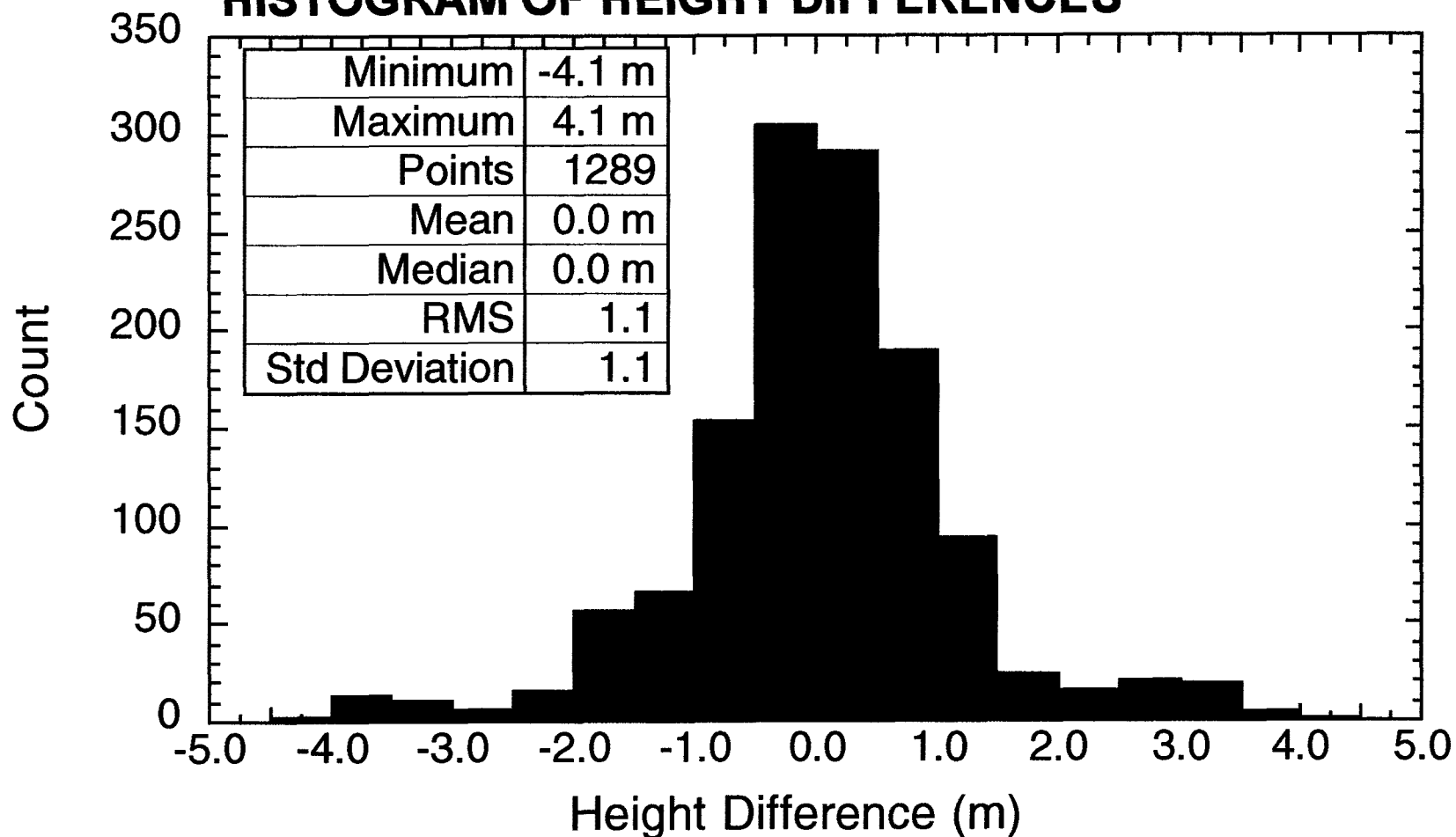
SRTM Orbit Overlaps

Av. Phase(LC) RMS: 1.7 cm, Av. %Outliers: 8.7

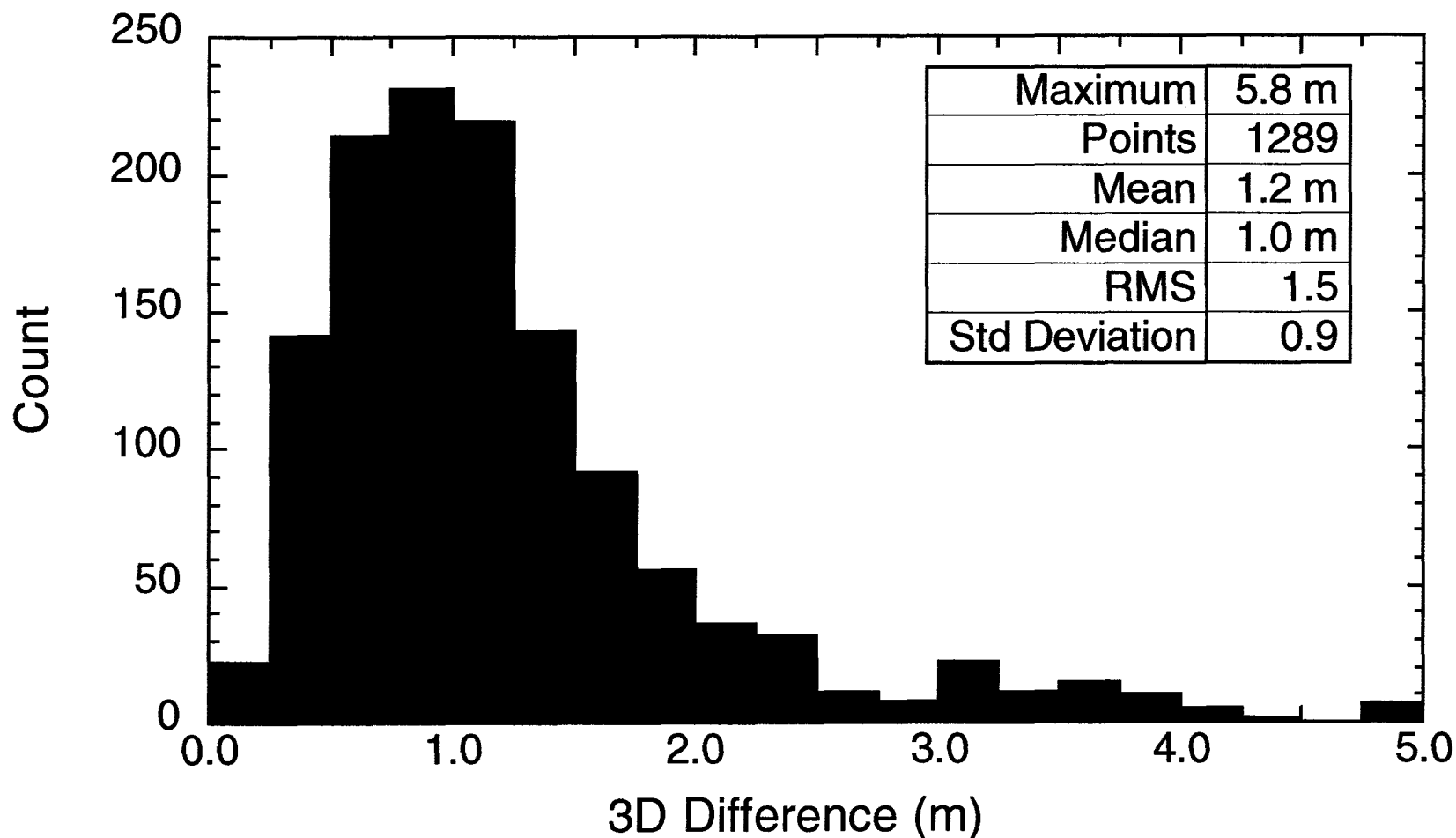**Av. Range(PC) RMS: 1.1 m, Av. %Outliers: 12.6**

- **Reduced Dynamics: 1 m/sec^2 white noise stochastic accelerations (nominal strategy 2.5E-6 m/sec^2 15 hr time constant)**

- **Take only points with 3D formal errors < 50 cm**

- **Errors**

    - **Short Phase Arcs => range errors dominate**

        - **Nudge**

        - **Multipath**

    - **Error, probably > nominal reduced dynamics**

HISTOGRAM OF HEIGHT DIFFERENCES

Minimum	-4.1 m
Maximum	4.1 m
Points	1289
Mean	0.0 m
Median	0.0 m
RMS	1.1
Std Deviation	1.1

Height Difference (m)

Count

HISTOGRAM OF 3D ORBIT DIFFERENCES

Maximum	5.8 m
Points	1289
Mean	1.2 m
Median	1.0 m
RMS	1.5
Std Deviation	0.9

MAGR — BlackJack

3-hr MAGR data gap

Radial: Av. 2.3 m
Cross Track: Av. 1.8 m
Along Track: Av. 3.1 m

RMS Diff (meters)

Feb Day: Arc #
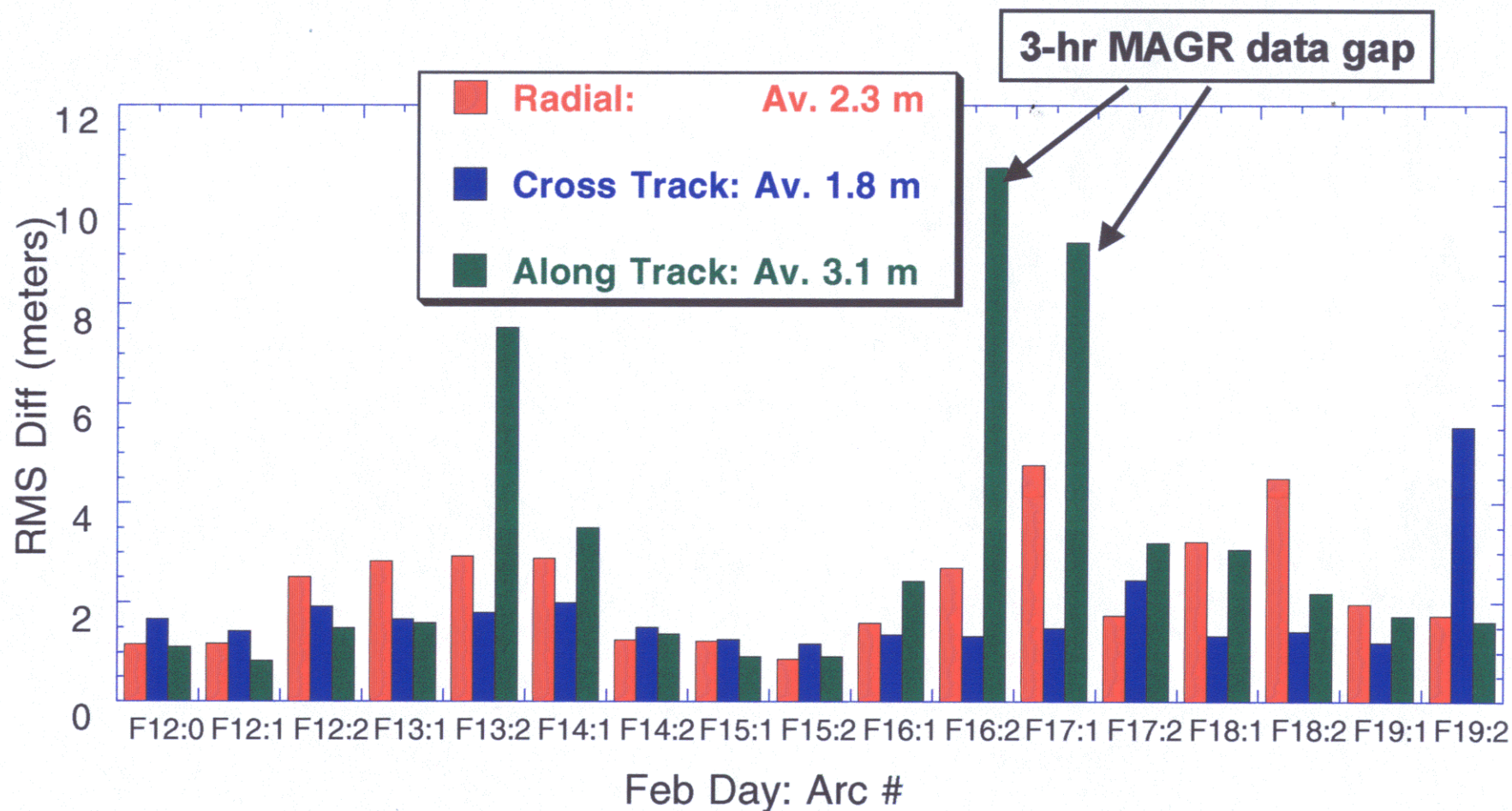
- **Delete 2 10-minute periods of best coverage**

    - **super-edit set**

    - **RMS Reduced-Dynamic differences 4-20 cm (mostly mean)**

    - **Super-edit difference: RMS 70-80 cm (per component)**

- **Delete 30 minute segment near arc edge**

    - **RMS of 73, 92, and 180 cm — Radial, Cross, Along**

JPL

CHAMP On-Orbit Preliminary Performance
450 km Altitude

- 4 days of data processed (27 hour arcs)

- RMS overlaps < 10 cm

Laser Residuals, Independent Verification

Site	Number of 5 Second Points	Mean(cm)	Standard Deviation(cm)
Grasse, France	54	9.8	6.6
Yaragadee, Australia	17	-1.5	2.6

September 21, 2000   ION GPS 2000, Space Systems and Applications   Willy Bertiger

JPL

- **100% coverage of radar data takes with 2 receiver reduced dynamic orbits**

- **60 cm accuracy requirement is met with 2 BlackJack solutions**

  - Overlaps < 50 cm; 1.7 cm phase residuals; MAGR comparisons

- **BlackJack Future is bright**

  - CHAMP orbits < 10 cm at 450 km